ATMOSPHERIC AND OCEANIC SCIENCES RESEARCH PROGRAM

Technical Report

NOAA Cooperative Agreement # NA17RJ2612

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RESEARCH ACTIVITIES

This report highlights several of the important research activities carried out during the period, July 1, 2002 through May 31, 2003 under NOAA's Co-operative agreement #NA17RJ2612, "The Atmospheric and Oceanic Sciences (AOS) Research Program." This research program is a cooperative agreement between Princeton University and the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA). The report lists papers, published in refereed journals and submitted for publication, that describe research supported under this program. The report also provides a list of Program Scientists and Assistants-in-Research supported by the grant for this period and a summary of travel activities supported by the program during the period. The research program supports research determined by Princeton University to be vital to its Atmospheric and Oceanic Sciences Program and determined by NOAA to be consonant with its authorized mission.

Executive Summary

Research undertaken thus far has focused on studies of the climate system and its subcomponents, and thus on climate variability and change, climate dynamics and climate prediction. Specifically, research has been undertaken to aid in addressing three elements of the "Environmental Assessment and Prediction" portfolio of the NOAA Strategic Plan, namely: to advance short-term warnings and forecasts; implement seasonal to interannual climate forecasts; and to predict and assess decadal-to-centennial change. To this end, research has been carried out in the following areas:

1. **Dynamics of global warming** – This has included estimating the long-term consequences of changes in atmospheric composition on the state of the atmosphere, oceans, ice, and land surface; and quantifying the uncertainties in these estimates.
2. **Dynamics of natural climate variability on decadal to centennial time scales** – This has included understanding low-frequency variability in the atmosphere; El Niño-Southern Oscillation (ENSO); the North Atlantic Oscillation (NAO); multi-decadal oceanic variability; and how global warming will impact these and other natural climatic fluctuations.
3. **Ocean dynamics, and the role of the ocean in the climate system and in climate change** – This area has included research on oceanic mesoscale dynamics, and the development of parameterizations of unresolved processes in the ocean.
4. **Research on the radiative properties of the atmosphere, including active trace gases, aerosols, clouds, and convection** – This has included research on the carbon cycle in the atmosphere, ocean and biosphere; predictions of future atmospheric composition; and identifying and modeling sources and sinks of carbon on land and in the ocean.

A large variety of projects were initiated, continued and or concluded this past year. Much of the work has been undertaken by postdoctoral research fellows, scientific visitors and students, supervised and working with permanent members of the GFDL scientific staff or faculty at Princeton University's AOS program. A number of publications in the peer-reviewed scientific literature have ensued, as detailed below. In addition, in many cases the knowledge gained has or will be incorporated into the design and implementation of numerical models of the atmosphere-ocean-land surface system, thus potentially improving our ability to predict the climate system on timescales from the daily to the centennial.

Detailed Reports of Supported Students

The General Circulation of the Atmosphere
Nadejda Grianik
Advisor: Geoffrey Vallis

This work is concerned with the development of a closed statistical model, based on scale analysis And nonlinear dynamics, for the general circulation of the troposphere. The model will explain qualitatively the basic features of the turbulent regimes simulated using a simplified atmospheric general circulation model; the features are such as variations in the scales of the jet and the eddies, and lack of clear inverse energy cascade in the energy spectrum.

The recent achievements include the generation of the regimes with multiple baroclinic zones and multiple jets in response to the increase in the rotation rate of the planet. These simulations indicate that isentropes do not universally pass from the equatorial surface to the polar tropopause if multiple baroclinic zones are present. We are currently testing some of the scaling assumptions and predictions of the theory.

Studies in Atmospheric Data Assimilation
Shree Khare
Advisor: Jeffery Anderson

Research activities over the past year can be broadly summarized in the following three categories:

(1) -- Theoretical investigation of ensemble filter based methodologies for targeted observations

(2) -- Investigation of ensemble filter based targeted observation strategies in a low order dynamic system

(3) -- Exploration of novel methodologies for the design of routine observing systems. The central theme of the research being undertaken is to investigate the optimal design of targeted and fixed (in space) observing systems when doing ensemble prediction of geophysical flows. (The goal of targeting observations is to identify locations in space at a future time where observations can be placed that will improve forecasts of features at times even farther into the future. Within the framework of an ensemble filter, a novel scheme for targeting observations has been developed. The scheme is called the Gaussian Joint State Observation (GJSO) method. The relationship to the scheme used operationally at NCEP, the Ensemble Transform Kalman Filter technique (Bishop et al. 2001 - MWR), has been explored. The conditions for which the GJSO and ETKF targeting schemes are equivalent and non-equivalent have been derived. For the cases where the two methods are equivalent, the GJSO method provides a new framework for understanding the approximations inherent to the ETKF. The GJSO method generalizes the ETKF method to the case of non linear observation operators.
Additional theoretical investigation of ensemble filter based methodologies has been undertaken. This work has resulted in the derivation of several novel methodologies for targeting

observations. In particular, a scheme called the Uncertainty method has been derived. The Uncertainty scheme is an algorithm for computing the most general possible estimate of the forecast variance at the verification time under the influence of hypothetical observations at the targeting time.

The performance of several ensemble filter based targeting schemes has also been examined in observing system simulation experiments using the Lorenz 1996 model and an ensemble filter for data assimilation. The goal of this investigation has been to use a simplified model/observing system setting to achieve maximum understanding of the various targeting methologies tested. We have provided a clear demonstration of the role of the model dynamics in selecting locations of targeted observations

Hygroscopicity of organic carbon aerosols and their radiative effects
Cynthia Randles
Advisor: V. Ramaswamy

This project has involved determining the growth of various types of organic aerosols at relative humidities ranging from 20 to 100% using the Princeton aerosol growth model. Current species investigated are glutaric and succinic acid mixtures with sea-salt particles. Such mixtures are observed in the present-day atmosphere, and increase in their organic carbon content is expected owing to increased anthropogenic activities. For any relative humidity, the size of a pure sea-salt particle is larger than that for particles mixed with organic carbon. The organics reduce the hygroscopicity. These model calculations are somewhat substantiated by observations of sizes of particles in pristine and polluted atmospheres. The contrast between the growth of an initial dry aerosol mass of pure sea-salt versus a sea-salt-organic-carbon mixture becomes sharper at relative humidities greater than 80%. Because organic carbon is mildly absorbing whereas a pure sea-salt aerosol is nonabsorbing, the presence of organic carbon content signifies greater absorption by the aerosol particle mixtures. However, this is tempered by the fact that the size of pure sea-salt particles at a particular humidity is larger than that with mixtures of organic carbon, and by the fact that a smaller size means lesser optical cross-section and hence a lesser absorption. Thus, the overall effect of organic carbon relative to pure sea-salt aerosols on the absorption of light depends on the amount of organics and the relative humidities.

Modulation of Transient Eddy Activities by ENSO
Francis Tam
Advisor: Ngar-Cheung Lau

Some detailed studies of how ENSO affects extratropical low-frequency circulation anomalies have been carried out. Motivated by the fact that North Pacific low-frequency perturbations are more active during cold ENSO phase, their life cycles are examined, assisted with wave-activity flux diagnostics during their evolution. Analyses reveal stronger activities originating from the subtropical ocean during cold ENSO events, when anomalies over North Pacific begin to grow. Locally, vertical activity fluxes from low levels are also enhanced, especially in high latitudes, indicating the presence of stronger baroclinic sources. Activity vectors also show a more

prominent downstream dispersion of waves from the North Pacific anomalous ridge to the northwestern American seaboard. Results from GCM experiments and NCEP-NCAR reanalyses are in good agreement concerning the above ENSO modulations.

The problem of how ENSO affects tropical synoptic-scale activities during boreal summer has been revisited. Based on both GCM and reanalyses data, activities are found to be located more eastward during the warm ENSO phase, compared with the climatological situation. Geographical locations of genesis and subsequent tracks of these synoptic-scale perturbations also change. Over central-western equatorial Pacific, TD-type disturbances with a distinct horizontal tilt and meridional propagation are found to be emanated from equatorial mixed Rossby-gravity (MRG) waves, which experience a rapid decrease of wave scale as they propagate westward. Such wave emanation into the western Pacific basin is located differently during different ENSO phases. There are also some significant differences of amplitudes of MRG waves along a broad equatorial zone; this is accompanied by changes of their group velocities as well. By considering theoretical dispersion curves and variation of scales of waves, these impacts can be related to the ENSO modulation of the ambient flow.

Black Carbon
Huiyan Yang
Advisor: Chip Levy and Larry Horovitz

After running a global simulation of BC with the GFDL GCTM last summer, I examined the microphysics of BC. I simulated the variation of BC physical properties and their impact on transportation and conversion process in a simple box model. I also tested dry deposition, and the (size) growth of BC in a humid environment.

We have also examined the health impacts of soot and BC, and the distribution infrastructure of LPG (Liquified Petroleum Gas), which can be used for another clean fuel DME (dimethylether) that can be synthesized from coal, biomass, or natural gas.

Work has also proceeded on the development of a module for the fast calculation of photodissociation [fast-J] The current scheme uses a fine wavelength resolution, which has around 100 wavelength intervals from 180nm to 850nm, and will be a big burden for global modeling. The fast-J scheme uses 10 wavelength bins from 285nm to 735nm, which is designed for troposphere and lower stratosphere chemistry. The primary results show that the scheme is capable of calculating the important J values of most species that are frequently seen in the troposphere, with an accuracy better than 5% for most cases when compared with the high resolution 1nm-bin model. The one exception is at very large solar zenith angles, when photodissociation is quite small. The variation of the vertical ozone profile, surface albedo, cloud, and aerosol can be easily included in the scheme. The next step to integrate the scheme into MOZART and the GFDL-GCTM, both of which currently use interpolation table for J values.

Detailed Reports of Supported Scientists

Forward modeling of open-ocean tides and tidal dissipation
Brian Arbic
Avisor: Steve Garner

Open-ocean tidal elevations have been mapped to high accuracy, with rms errors of order one centimeter, in models constrained by satellite altimetry data. Egbert and Ray (2000,2001) inferred from data-constrained models that about 25 to 30 percent of the total tidal energy dissipation occurs in the deep ocean. This suggests that tides may be an important source of energy for mixing, and hence, affect the large-scale overturning circulation (Munk and Wunsch 1998). Open-ocean tidal dissipation occurs largely over regions of rough topography (Polzin et al. 1997). Jayne and St. Laurent (2001) showed that the accuracy of forward simulations of the tides is improved when a parameterization of wave drag over rough topogragraphy is included.

Our work builds upon that of Jayne and St. Laurent. A parameterization scheme developed for atmospheric flow over rough topography (Garner 2003, submitted) has been adapted to the tidal problem. The scheme can handle arbitrary topography and has an order one tunable parameter. Tidal amplitudes are sensitive to this parameter--they are too low if there is too much drag, and too high if there is too little. We tune the parameter in order to minimize the misfit between our model and observations. As far as we know, ours is the most accurate "first-principles" simulation of the tides.

Since tides are so precisely known, they serve as a useful laboratory for the effects of topography and topographic dissipation on geophysical flows. It is likely that rough topography is an important energy sink for mesoscale eddies (Gille et al. 2000), and other investigators at GFDL, inspired in part by our work, have shown that the large-scale circulation also appears to be sensitive to topographic dissipation. We have used the tides to test the quality of the recently released GEBCO bathymetric dataset. Tidal accuracies are somewhat worse that those obtained with the older Smith and Sandwell (1997) dataset.

Once we have tuned the dissipation parameter against the observed tides, our model cab be used to study paleo-tides. Both abyssal and total tidal dissipations appear to have been larger during the last glacial maximum. This has implications for the solid-earth geophysics community as well as for oceanographers.

We have performed the first global simulation of baroclinic tides, and find that including stratification improves the accuracy of the surface tidal elevations. Future work on baroclinic tides will be carried out by Harper Simmons.

This work has brought the primary investigator (Arbic) into contact with the solid earth geophysics community. Professor Jerry Mitrovica is currently carrying out calculations of the deformation of a laterally heterogeneous earth model by ocean load tides. It is hoped that accounting for these heterogeneties will improve the accuracy of our ocean tide simulations. Professor Douglas MacAyeal is quite interested in the last glacial maximum simulation, since tides have important effects on the polar ice sheets.

The work has taken longer to complete than originally hoped, but final runs are being done and papers are being written. It is probable that one long paper and a few short ones will come out of this project.

The dynamical effect of the Bering Strait on the large scale ocean circulation
Agatha deBoer
Advisor: Robert Toggweiler, Danny Sigman, Anand Gnanadesikan

The Holocene interglacial period of the last 10,000 years and the penultimate interglacial ~125,000 years ago have been characterized by distinctly stable climates. During the intervening glacial period, climate records are marked by large-amplitude oscillations, generally known as Dansgaard-Oeschger or Heinrich events. These millennial-scale cycles are generally believed to be a result of freshwater anomalies in the North-Atlantic, followed by a reorganization of the thermohaline circulation. Previous analytical work by De Boer and Nof suggests that such long lasting instabilities in the thermohaline circulation are only possible during glacial periods when the Bering Strait (BS) is closed. They argue that, during interglacial periods (when the BS is open) perturbations in North Atlantic Deep Water (NADW) formation are rapidly damped out because of a novel BS freshwater feedback mechanism. This new feedback mechanism is due to the strong winds in the Southern Ocean (SO) which, with an open BS, quickly [O(1-10 years)] flush any low salinity anomalies out of the Atlantic and into the Pacific Ocean. During glacial periods, the stabilizing feedback is prevented by the closure of the BS which traps the anomalies within the Atlantic, causing long lasting perturbations.

We have begun a program to test this hypothesis in an Ocean General Circulation Model coupled to an Energy Balance Model. The model will be run to a steady state for both an open and closed Bering Strait case. Next, the freshwater over the North-Atlantic will be increased until the meridional overturning ceases. The recovery from this state will be compared for the two geometries. As a second step we will test the effect of stronger and weaker wind forcings and also increase the albedo to simulate the glacial climate closer.

Another feature of the closed Bering Strait regime is an increased transport of upper water from the Indo-Pacific to the Atlantic via the ACC. The transfer is strongest when strong winds are applied in the south and when there is vigorous deep-water formation in the North Atlantic. It is weakened when deep water formation in the Atlantic is suppressed. An increase in the interbasin transport causes upward doming of isopycnals in the thermocline of the Tropical Pacific. As part of the proposed project, we would like to determine if the decrease in thermocline depth during times of vigorous deep water formation in the North-Atlantic may explain the tight coupling between the oxygen variation found in the Behl and Kennett observations and temperatures derived from the Greenland ice core record.

Preliminary numerical experiments exhibit an unrealistic large flow through the open strait and reproduce present day ocean features much better when the strait is closed. We plan to improve the Bering Strait constraint in the "Water Planet" model in order to obtain a more realistic present day solution. The model can then be used to determine the extent of the control of the strait and address the application to climate.

The roles of eddies at separated boundary currents: transports and stratification effects
Baylor Fox-Kemper
Advisor: Geoff Vallis

We are investigating the role of mesoscale eddies in the Gulf Stream separation problem, and also in the thermodynamic balance of the subtropical gyres. The primary tool is an isopycnal model developed by R. Hallberg. This work is in the very earliest stages, although we are already running the model on example problems. The model can be integrated with very small diffusivity, and the integral balances can be easily evaluated. The goal is to connect the essentially thermodynamic approaches of Parsons and descendants with more recent dynamical considerations.

Radiation studies using satellite data
Fei Liu
Advisor: V. Ramaswamy

The MODerate resolution Imaging Spectroradiometer (MODIS) on board of TERRA satellite and Advanced Very High Resolution Radiometer (AVHRR) on board of NOAA-16 satellite, together with ground based AErosol RObotic NETwork (AERONET), provide global aerosol optical depth (AOD) measurement. Geophysical Fluid Dynamics Lab (GFDL) General Circulation Model (GCM) aerosol climatology is evaluated against the measurements. AOD retrieved from MODIS is consistently larger than what AVHRR measures over oceans by 0.1 and overall larger than GCM prediction by 0.07. Comparison between 20 AERONET stations and corresponding MODIS regional averaged AOD show good overall agreement. Both MODIS and AVHRR capture the seasonal variation of aerosol loading near eastern U.S., eastern China, Arabian Sea, and India. The seasonal cycles are also observed at individual AERONET stations with locality signature over regional average. The GCM captures the seasonal variation of aerosol loading near Arabian Sea, but near the other regions the GCM sulfate aerosol parameterization is affected by winter time Northern Hemisphere storm system and the GCM show significant deviation from satellite measurements at winter time and early spring.

Dynamics of Convection
Olivier Pauluis
Advisor: Issac Held

A large portion of this work has been centered on the development of a non-hydrostatic model, in collaboration with Steve Garner and Chris Kerr. A new microphysics package and a new set of diagnostics have been implemented, while the model is currently being modified to fit into the FMS standard. Several experiments have been performed, both to test the model behavior and to study different scientific issues. Several radiative-convective equilibrium simulations have been conducted to investigate the sensitivity to the amount of water vapor present in the atmosphere. A high-resolution simulation of a Walker circulation is under way. This simulation uses a 2km

horizontal resolution to explicitly resolve convection on a 6000km x 150 km domain, and could be directly compared with a result from a GCM using parameterized convection.
The next stage will start once the non-hydrostatic model would have been made fully compatible with the FMS standard, and would then be able to use the GFDL radiation package. Several experiments are planned such as radiative-convective equilibrium with interactive radiation, and a comparison with the WRF model based on TOGA-COARE experiment. Further developments include the use of more sophisticated parameterization for shallow parameterization and a thee dimensional turbulence closure scheme.

Other work, in collaboration with Dargan Frierson and Isaac Held, involves using an idealized GCM based on the FMS spectral core. One of our goals is to investigate the sensitivity of a GCM to the representation of deep convection. This is motivated by a comparison between two different schemes, the Moist Convective Adjustment (MCA) and Relaxed Arakawa-Schubert (RAS), which has shown striking differences between the atmospheric circulations. In the first stage of this project, we are developing a set of convection parameterizations designed to be as simple as possible and that include only a few controlling parameters. Once this is achieved, we will investigate the sensitivity of various aspects of the atmospheric circulation, such as tropical wave dynamics, multiple ITCZ, and moist baroclinic eddies.

Representation of Convection in Climate Models
Vaughan Phillips
Advisor: Leo Donner

A novel closure assumption by Dr Guang Zhang for the statistical representation of deep convection in global climate models (GCMs) is being tested. This hypothesis states that deep convection exists in a slowly evolving balance with the component of the large-scale forcing due to the free troposphere. We have discovered that this closure is widely applicable to ocean and land regions. We have performed a set of simulations to test the sensitivity of the convective field to the time-scale of variability of the large-scale forcing with the Weather, Research and Forecasting Model (WRF), and we are applying WRF to investigate the physical reasons for validity of Guang's closure.

A super-parameterisation approach to representing convection is currently being developed by several research groups and we are participating in this. A cloud-resolving model is embedded within each grid-box of the GCM according to this technique. An important issue is whether this cloud-resolving model ought to be 3-D or 2-D, and whether the orientation of the 2-D model is important. Recently I have applied WRF to research the sensitivity of the convective field to the choice of dimensionality of the domain. I have performed and analysed comparisons between 2-D and 3-D simulations that contain the same number of grid-columns (7225). An ensemble of (85) 2-D simulations that each has a lower number of grid-columns (85) is now being processed, to investigate whether the large 2-D simulation evolves differently for statistical reasons, with its larger sample of clouds. The apparent heat source, apparent moisture sink and horizontal momentum flux are all key quantities for this analysis. We have also been improving the representation of microphysical processes in our explicit microphysics model this year, by incorporating advanced treatments of coalescence, drop break-up, aggregation, CCN

advection, homogeneous freezing of CCN and droplet nucleation with assistance from Professor Alex Khain. Simulations of a storm observed on the 7th July 2002 with the microphysical model, which has been initialised with observed CCN distributions provided by Dr Bill Conant and observed dynamics, have already reproduced observed microphysical features in the cloud.

Dynamical mechanisms and diagnosis of stratospheric influences on the troposphere
Thomas Reichler
Advisor: Paul Kushner

There is increasing evidence that stratospheric processes influence the tropospheric circulation across a wide range of timescales. On intraseasonal timescales, observations show that anomalies of the Northern Hemisphere wintertime stratospheric polar vortex frequently precede persistent changes to the tropospheric circulation that resemble the Arctic Oscillation. This may be useful in improving the predictability of the extratropical troposphere on time scales of the order of several weeks. The tropospheric circulation may also be linked to the stratosphere on longer timescales. For example, it has been found that stratospheric forcings in relationship with ozone depletion, volcanic aerosols, or the quasi-biennial oscillation exhibit a signature in surface climate. Such a coupling may be important for more realistic simulations of anthropogenic climate change in relationship with secular changes of greenhouse gases.

The dynamical mechanisms by which stratospheric circulation anomalies can influence the troposphere are poorly understood, and most current numerical models for weather or climate do not include a well-resolved stratosphere. The objective of this research is to better understand the role of the stratosphere for tropospheric weather and climate with a numerical model that specifically resolves middle atmospheric dynamics. In continuation of earlier work by Polvani and Kushner (2002) and Kushner and Polvani (2003) we want to use the same model as in those previous studies. The dry hydrostatic primitive equation model of the troposphere-stratosphere system will be used to conduct sensitivity experiments to transient forcings. The use of this relatively simple model allows the careful examination of the mechanisms that control the wave flux into the stratosphere as well as the downward propagation following major stratospheric circulation anomalies.

As a first approach we want to investigate the response of the model to transient wave activity flux from the troposphere. A recent observational study by Polvani and Waugh (2003) indicates that the eddy heat flux at the tropopause correlates well with the zonal mean winds in the middle stratosphere, indicating that stratospheric anomalies are controlled by anomalous wave activity fluxes from the troposphere. It is unclear, however, whether the stratosphere simply responds to upward wave activity fluxes from the troposphere, or actually modulates such wave activity fluxes. In our model experiments, pulses of upward propagating planetary waves are created by prescribing a time varying bottom topography to the model at the beginning of the simulation. The waves break in the stratosphere and lead to zonal wind anomalies also known as stratospheric warming events. This experimental setup allows us to create controlled stratospheric circulation anomalies and to investigate their subsequent downward propagation into the troposphere. The results can be used to understand the sensitivity of the stratosphere to tropospheric wave activity flux, to find out the optimal conditions for the creation of sudden

warmings, and to investigate the nature of the subsequent tropospheric response. It will be particularly interesting to compare the results with those from unforced simulations, and to find out how important antecedent tropospheric wave forcing is for the subsequent downward propagating of circulation anomalies.

Links Between Atmospheric Annular Modes and Carbon Sequestration in the Ocean
Joellen Russell
Advisor: Robbie Toggweiler

The ocean's role in the global carbon cycle is still uncertain. Carbon dioxide is absorbed by the ocean at middle and high latitudes and is sequestered away from the surface by both biological activity and subsurface water mass formation. Depending on a water parcel's history, it may be undersaturated to varying degrees when exposed to the surface, and may or may not come into equilibrium before it leaves the surface. Recent evidence has shown that North Pacific Intermediate waters are undersaturated with respect to chlorofluorocarbons when the waters are subducted and that the degree of undersaturation may vary from year to year (Sonnerup, et al., 1999). This variability is likely due to changes in both the wind stress and the depth of the winter-time mixed layer. The mid-latitude wind stresses over the North Pacific and Southern Ocean have been shown to covary with the indices of the Northern Annular Mode (NAM) and the Southern Annular Mode (SAM), respectively. These indices have been trending to their positive polarity, possibly due to anthropogenic warming of the troposphere. We am currently working to couple an atmospheric energy balance model (EBM) to the Inchon version of MOM4. The main advantage of the EBM is that it determines the various components of the air-sea heat and fresh water fluxes without specifying a target SST or SSS value. This allows for the development of both short- and long-lived temperature and salinity deviations from the climatology. We are also in the process of incorporating a simplified carbon cycle model based on OCMIP into this coupled system, based on previous work done by Steve Carson and Robbie Toggweiler

Our goal is to simulate the effect of a trend in the annular modes by imposing wind anomalies in the shape and magnitude implied by the trend in the NAM and SAM. After imposing wind anomalies equal to the 2-sigma level of the AO and AAO (separately and together) for both the high- and low-index state, we study the carbon transport by the model's intermediate and mode waters under the nominal CO2 forcing and a doubled CO2 forcing. These studies are just beginning, and will have implications for the global carbon cycle in both the past (i.e. glacial-interglacial) and the future (as a response to increased greenhouse gas loading).

Dynamics of the Antarctic Circumpolar Current
Che Sun
Advisor: Robert Hallberg

We have been working on the adiabatic mechanisms in relation to the meridional overturning cell of the ACC. A series of eddy-resolving experiments, from flat-bottom to realistic topography, have been carried out using the HIM model. The study suggests a continuously

stratified fluid at its adiabatic equilibrium does not permit meridional overturning motions; the surface Ekman transport ceases to exist as isopycnals outcrop; for the flat-bottom case, there exists an interannual mass oscillation in the outcropping layers which largely compensates the variation in the bottom layer; the interior layers have little meridional mass shift and exhibit relatively uniform IPV, and little potential energy associated with the thickness gradient is released during no-wind adjustment.

Additional experiment will be conducted to examine how topography and horizontal resolution would affect the final equilibrium. Although the idealistic study represents an adiabatic extreme, it may hold pertinence to the Southern Ocean in areas like form drag and dominant modes.

Biogeochemical tracers in ocean models
Colm Sweeney
Advisor: Tony Rosati

We have been looking at the effects due to difference parameterizations of shortwave irradiance in the water column on ocean circulation and heat transport. The results of this study show that parameterizations which prescribe more absorption of shortwave irradiance at the surface tend to stratify the waters in the subtropical and tropical gyre regions. The effect of this stratification actually results in small increases in heat transport due to a shallower Ekman layer and greater surface divergence. The resulting effect at the equator is lower sea surface temperatures. While the addition to chlorophyll-a fields to the MOM4 ocean model has added another level of realism our parameterization of shortwave radiation, the overall effects to circulation are second order.

We are also involved in the estimation of pCO2 in the equatorial Pacific using the Rosati assimilation model and Feely pCO2 data. This project is a part of an effort by Ants Leetma to try to establish a link between AOML/PMEL and GFDL which would integrate carbon modeling and carbon measurement efforts throughout the world oceans. We organized a data assimilation workshop in which we set several projects to be worked on in our collaboration between AOML and PMEL. Among the projects were the following:
a) Using the GFDL 3D VAR data assimilation model in concert with surface data collected in Equatorial Pacific to improve empirical estimates of surface water pCO2.
b) Investigating whether the adjoint of a simplified model of MOM4 circulation can be used to do variational assimilation of ecological data and estimate the interannual variability of surface water pCO2. Current plans for this pilot project are to optimize the parameters of simple three-component ecological model by assimilating SeaWiFS ocean color and climatological nutrient concentrations. If the use of a simplified circulation adjoint is successful, more realistic ecological models could be used.
c) Implementing John Dunne's ecosystem model in the high resolution version of MOM4, OM3 forced by re-analysis data from the last 50 years. At present, I have made very little progress on this model because the tracer code for nutrients and CO2 is still pending. However, both the tracer code and John Dunne's ecosystem model are rapidly coming together. This project will involve extensive analysis of carbon and nutrient fields in comparison with observations.

The Diurnal Cycle of Convection, Clouds, and Water Vapor in the Tropical Upper Troposphere: Satellites vs. a GCM
Baijun Tian
Advisor: Brian Soden

The diurnal cycle of hydrological cycle is one of the fundamental modes of variability of the global climate system and has been extensively studied for several decades. However, there are few studies of the diurnal cycle of water vapor, which is directly associated with the hydrological cycle. Second, for the purpose of GCM development, many studies have demonstrated that an accurate representation of the diurnal cycle of convection, clouds and water vapor provides a key test of many aspects of the physical parameterizations in a GCM, such as convection, cloud and radiative transfer processes.

Motivated by these two points, a global archive of high-resolution (3-hourly, 0.1x0.1 longitude-latitude pixel) data of 11 and 6.7 micro brightness temperatures (TB11 and TB67) from multiple geostationary satellites are used to document the diurnal cycle of deep convection (DC), cloud (CLD) and water vapor (UTH) in the tropical upper troposphere and to evaluate the ability of the new GFDL global atmosphere and land model known as "AM2/LM2" in simulating these diurnal variations.

The characteristics of the diurnal cycle based on the satellite data agree with previous observational studies, featuring a clear land-sea contrast in the diurnal cycle in DC and CLD, which is stronger over land and weaker over ocean. It is shown that continental convection generally peaks in the later afternoon and early evening, while oceanic convection tends to reach maximum in the early morning. High clouds over land generally peak in the late evening, while they tends to reach maximum in the later afternoon over ocean. However, UTH tends to peaks in midnight over both land and ocean. The phase lag between UTH, CLD and DC is large over ocean and small over land.

Compared to observations, AM2 can reasonably simulate the diurnal phase of deep convection, high clouds and UTH over land although the magnitude is noticeably weaker in the model. The model also has considerable difficulty in capturing the diurnal cycle of deep convection, high clouds and UTH over the oceans. First, the diurnal magnitudes are severely underestimated possible due to the specified SST without any diurnal cycle. Second, the modeled high clouds is nearly 12 hours out of phase with observations. This suggests some fundamental deficiencies in the model's physical parameterizations, such as convection and cloud parameterizations, especially over ocean.

Atmospheric and Oceanic Dynamics
Geoffrey K. Vallis

Vallis continues to study variety of problems in atmospheric and oceanic dynamics, as well as supervising the research of some of the students and postdoctoral researchers mentioned in this grant, and performing a variety of coordination and administrative duties involving GFDL and the University. On the oceanographic side, we have investigated the effects of mesoscale eddies on the structure of the stratification of the ocean. These problems are being investigated using

various idealized ocean models, and more realistic simulations of the Southern Ocean. We have also investigated the mechanisms of Gulf Stream separation, and problems of decadal variability of the ocean. On the atmospheric side, we are continuing to develop a theory of the dynamics of the North Atlantic Oscillation and so-called Annular modes. Finally, we are exploring new parameterizations of ocean eddies.

Seasonal-to-Interannual Climate Variability and Prediction
Andrew Wittenberg
Advisor: Anthony Rosati and Matthew Harrison

Tropical Pacific seasonal-to-interannual (SI) climate variations affect weather, ecosystems, and economies worldwide. Yet predicting these variations remains a challenge for the atmospheric and oceanic sciences, due to complex interactions among multiple scales that are not well understood. Three elements are key to achieving more useful SI predictions: (1) improved forecast models, (2) more accurate initial conditions, and (3) better representation of forecast uncertainties. Each in turn benefits from improved understanding, which requires diagnostic and modeling studies and comprehensive observational analyses. Our research encompasses each of these elements.

For example, we have examined tropical Pacific surface observations over the past four decades, advanced a statistical/dynamical model of El Nino, and used theoretical and GCM results to explain why ENSO behavior and predictability are sensitive to the tropical climatology.

Current activities include:

1) Developing a statistical/dynamical hybrid coupled GCM and using it to explore how model formulation, assimilation procedures, and stochastic forcing affect the simulation and prediction of ENSO. We have completed a statistical model of momentum, heat, and water fluxes at the ocean surface and coupled it to an global version of the GFDL Modular Ocean Model version 4 (MOM4). The statistical model includes both deterministic and stochastic components, and provides a convenient testbed for data assimilation, and SI forecasts. We have delivered the hybrid coupled model to the International Research Institute for use in their SI research and forecasts, and continue to work closely with IRI on its improvement. The hybrid model is also proving valuable for testing theories of intraseasonal/ENSO interactions, in collaborative work with scientists from the University of Miami / RSMAS and the University of Colorado at Boulder. At GFDL, the model will be used in experiments designed to elucidate the influence of sea surface temperatures, initial conditions, weather noise, and nonlinearity on SI forecasts.

2) Evaluating the tropical Pacific behavior of atmospheric, oceanic, and coupled GCMs under development at GFDL.

3) Defining a framework for importing, quality-controlling, and assimilating observational data into ocean models at NOAA's Applied Research Centers (ARCs). The long-term goal is a flexible, web-based system that will support operational forecasts by operating automatically and in near-real time. Special attention is being paid to the instrumental source of each measurement, its quality and physical consistency, and likelihood function.

4) Building an adjoint model for MOM4: We are investigating the compatibility of the MOM4 Fortran-90 code with the TAF (Transformation of Algorithms in Fortran) adjoint compiler.

Mechanism of Gulf Stream separation

Rong Zhang
Advisor: Geoff Vallis

We have studied three problems:

1. Gulf stream separation: The importance and challenge of Gulf Stream separation problem is a classical problem in physical oceanography. The Gulf Stream separation significantly affects the surface heat flux in the western mid-latitude North Atlantic by distributing warm salty water along the path of Gulf Stream and North Atlantic Current. The huge amount of surface heatflux near the western boundary area is very important for the coupled atmospheric-ocean climate system.

We have studied the problem with a simple coupled model, i.e., a one degree global ocean general circulation model (MOM4) coupled with an energy balance model (EBM) and a simple sea-ice model. Our numerical modeling results show that the North Atlantic circulation and Gulf Stream separation position are sensitive to the magnitude of lateral viscosity and strength of Deep western boundary current (DWBC). We have developed a simple theory for the mechanism of Gulf Stream separation. We found that the bottom vortex stretching induced by downslope DWBC is a key mechanism for the Gulf Stream separation and the presence of northern recirculation.

2. Mechanisms of decadal variability in the North Atlantic: The Thermohaline Circulation, Gulf Stream Separation, and Great Salinity Anomalies.
We have nvestigated the physical mechanisms of decadal variability in the North Atlantic ocean with the simple coupled model. Particularly, we focus on exploring the hypothesis that the persistent decadal-scale Great Salinity Anomaly (GSA) events serve as a significant source to such variability, through their modulation of the thermohaline circulation, DWBC and the path of Gulf Stream. Preliminary numerical experiments indicate that GSA events significantly weaken the thermohaline circulation, and thus the strength of DWBC on decadal timescales. We have found that the GSA events have as much if not more effect on decadal ocean variability than do changes in the wind forcing (e.g., variability in the North Atlantic Oscillation) and, on decadal timescales, have a much larger effect than do changes in radiative and surface heat flux changes due to increased greenhouse gases.

3. Decadal variability of global ocean heat content
Recently observational results show significant coherent decadal variability of ocean heat content in different ocean basins during the past decades (Levitus et al. 2000). We are currently studying the possible physical mechanisms of the decadal variability of ocean heat content by coupling an ocean general circulation model (MOM4) with an energy balance model (EBM) and a simple sea-ice model. We find that under anomalous radiative forcing induced by increasing

greenhouse gas, and with constant winds, the ocean heat content increases monotonically, without any decadal variability. When the model is forced with the observed wind stress and wind speed of the past decades (1946-1992), significant inhomogeneous subsurface temperature variation on decadal time scales are found, but the overall decadal variation of basin scale ocean heat content induced by the anomalous wind is small compared with observations. We then test the hypothesis that anomalous freshwater flux at high latitudes may play an important role in modulating the ocean heat content on decadal time scales. We assume that the anomalous freshwater fluxes are associated with anomalous sea level pressure at high latitudes. When the anomalous freshwater fluxes are included, the ocean heat content shows decadal variability comparable to that observed and, in certain circumstances, variability that is coherent among different ocean basins. The model results indicate that the anomalous freshwater flux at the high latitude ocean is a significant factor in causing ocean heat content variations, by modulating the anomalous SST and associated heat flux, on decadal time scales.

Publications and Manuscripts submitted under the Cooperative Agreement

Donner, L.J. and V.T.J. Phillips, 2003: Boundary layer control on convective available potential energy: implications for cumulus parametrisation. Submitted to *Journal of Geophysical Research.*

Fedorov, A. V., S.L. Harper, S.G. Philander, B. Winter, and A. T. Wittenberg, 2003: How predictable is El Nino? *Bull. Amer. Meteor. Soc.,* in press.

Holloway, T., H. Levy II, and G. Carmichael, 2002: Transfer of reactive nitrogen in Asia: development and evaluation of a source-receptor model. *Atmospheric Environment*, 36(26), 4251-4264.

GFDL's Global Atmospheric Model Development Team, 2002: The new GFDL global atmosphere and land model AM2/LM2: Evaluation with prescribed SST simulations. Submitted to *J. Climate.*

Pauluis, Olivier, 2003: Boundary layer dynamics and cross-equatorial Hadley circulation, submitted to *J. Atmos. Sci*

Pauluis, Olivier, and Kerry A. Emanuel, 2003: Numerical instability resulting from infrequent calculation of radiative heating. Submitted to *Monthly Weather Review.*

Phillips, V.T.J., Choularton, T.W., Blyth, A.M., and J. Latham, 2003: Simulations of the glaciation of a frontal mixed-phase cloud with the Explicit Microphysics Model (EMM). *Q. J. R. Meteorol. Soc*., 129, pp. 1351-1371

Phillips, V.T.J., Choularton, T.W., Blyth, A.M., and J. Latham, 2002: The influence of aerosol concentrations on the glaciation and precipitation of a cumulus cloud. Q. *J. R. Meteorol. Soc.,*128, pp. 951-971

Phillips, V.T.J., Blyth, A.M., Brown, P.R.A., Choularton, T.W., and J. Latham, 2001: The glaciation of a cumulus cloud over New Mexico. *Q. J. R. Meteorol. Soc.,* 127, pp. 1513-1534

Sweeney, C. 2003. The annual cycle of surface CO2 and O2 in the Ross Sea: A model for gas exchange on the continental shelves of Antarctica. Antarctic Research Series (In press).

Tian, B., and B. J. Soden, 2003: The diurnal cycle of upper tropospheric water vapor. 13th ARM Science Team Meeting, Broomfield, CO.

Tian, B., and B. J. Soden, 2003: The diurnal cycle of convection, clouds and water vapor in tropical upper troposphere: Satellites vs. a GCM. Manuscript under preparation.

Tian, B., and V. Ramanathan, 2003: A simple moist tropical atmosphere model: Role of cloud radiative forcing. *J. Climate*, 16, 2086-2092.

Vallis, G.K. E. Gerber, P. Kushner and B. Cash 2003. A mechanism and simple model of the NAO and annular modes. Submitted to *J. Atmos. Sci.*

Vallis, G.K. 2003. Mean and eddy dynamics of the main thermocline. In "Nonlinear Processes in Geophysical Fluid Dynamics" O. U. Velasco Fuentes, J. Sheinbaum and J. Ochoa (editors). Kluwer Academic Publishers. Dordrecht, The Netherlands (2003) 141-172.

Wittenberg, A. T., 2003: What is the wind stress over the tropical Pacific? Submitted to *J. Climate*.

Wittenberg, A. T., and M. J. Harrison, 2003: A baseline statistical model for tropical Pacific wind stress anomalies. 14th Conference on Atmospheric and Oceanic Fluid Dynamics, San Antonio, TX, June 9-13. Paper #P4.2.

Zhang, S., J. L. Anderson, A. Rosati, M. Harrison, S. P. Khare, and A. T. Wittenberg, 2003: Multiple time level adjustment for data assimilation. Submitted to *Tellus*.

AOS Program Scientists Supported Under Cooperative Agreement

July 1, 2002 – May 31, 2003

Name	Host	Appointment Begins	Ends
Arbic, Brian	Garner	3/1/2001	2/28/2003
DeBoer, Agatha	Toggweiler	3/6/2003	3/7/2004 *
Fox-Kemper, Baylor	Vallis	4/7/2003	4/7/2004 *
Kim, Byung-Gon	Klein	5/1/2003	5/1/2004 *
Lapeyre, Guillaume	Held	10/15/2000	10/16/2002
Liu, Fei	Ramaswamy	5/28/2002	1/05/2003
Pauluis, Olivier	Held	8/1/2002	
Phillips, Vaughn	Donner	5/1/2001	3/1/2004
Reichler, Thomas	Kushner	2/1/2003	2/1/2004 *
Russell, Joellen	Toggweiler	2/1/2003	2/1/2004 *
Sun, Che	Hallberg	5/1/2001	6/20/2003
Sweeney, Colm	Rosati	7/1/2002	7/1/2004
Tian, Baijun	Soden	7/1/2002	6/30/2004
Vallis, Geoffrey	Vallis	7/1/1998	- [1]
Wang, Hailan	Lau	9/25/2000	11/30/2002
Wittenberg, Andrew	Rosati	6/10/2002	6/10/2004
Zhang, Rong	Vallis	1/1/2002	12/31/2003

* Appointment is subject to possible renewal for a second year

[1] Salary supplement to other research support

Assistants in Research Supported Under the Cooperative Agreement

Summer, Fall and Spring Terms 2002-2003

Assistants in Research	Appointment		Advisor	
	Begins	Ends		
*ADHITYA, Anita	09/01/01	-	Ramaswamy	[partial support]
GRIANIK, Nadejda	08/01/98	-	Vallis	[partial support]
KHARE, Shree	09/01/00	-	Anderson	
RANDLES, Cynthia	09/01/01	-	Ramaswamy	[partial support]
TAM, Chi-Yung	08/10/98	-	Lau	
YANG, Huiyan	08/01/99	-	Levy	[partial support]

* minimal support: no report included

Summary of travel supported under the cooperative agreement

July 1, 2002 – May 31, 2003

Traveler	Destination	Start	End	Purpose of Travel	Domestic	Foreign
Wittenberg, Andrew	Boston, MA	8/20/2002	8/23/2002	Fall AGU Meeting	$ 270	
Pauluis, Olivier	Princeton, NJ	9/3/2002	9/3/2002	Relocation from Somerville, MA	$ 419	
Fox-Kemper, Baylor	Princeton, NJ	9/24/2002	9/27/2002	Present Seminar at GFDL	$ 270	
Russell, Joellen	Washington, D.C.	8/28/2002	9/3/2002	Relocation from Seattle, WA	$ 2,600	
Tian, Baijun	Princeton, NJ	6/30/2002	9/11/2002	Relocation from LaJolla, CA	$ 3,343	
Khare, Shree	Oregon	7/22/2002	8/3/2002	3rd International Summer School	$ 200	
Wittenberg, Andrew	San Francisco, CA	12/5/2002	12/11/2002	Fall AGU Meeting	$ 1,306	
Sweeney, Colm	San Francisco, CA	12/6/2002	12/10/2002	Fall AGU Meeting	$ 1,087	
Zhang, Rong	San Francisco, CA	12/5/2002	12/11/2002	Fall AGU Meeting	$ 1,264	
Wittenberg, Andrew	Miami, FL	2/16/2003	2/20/2003	RSMAS Meeting	$ 1,267	
Wang, Hailan	Long Beach, CA	2/9/2003	2/14/2003	AMS Annual Meeting	$ 1,470	
Reichler, Thomas	Princeton, NJ	1/26/2003	2/11/2003	Relocation from San Diego, CA	$ 2,834	
Tian, Baijun	Boomfield, CO	3/31/2003	4/3/2003	ARM Science Team Meeting	$ 985	
Wittenberg, Andrew	San Antonio, TX	6/9/2003	6/13/2003	Travel Advance for meeting	$ 1,000	
Arbic, Brian	Nice, France	4/4/2003	4/12/2003	AGU-EGS Meeting	$ -	$ 1,574
DeBoer, Agatha	Princeton, NJ	2/28/2003	3/7/2003	Relocation from Miami, FL	$ 1,096	

Traveler	Destination	Start	End	Purpose of Travel	Domestic	Foreign
Phillips, Vaughan	Nice, France	4/5/2003	4/18/2003	AGU-EGS Meeting		$ 1,243
Russell, Joellen	Nice, France	4/5/2003	4/17/2003	AGU-EGS Meeting	$ -	$ 1,764
Fox-Kemper, Baylor	Princeton, NJ	3/12/2003	3/12/2003	Relocation from Cambridge, MA	$ 950	
Kim, Byung-Gon	Princeton, NJ	4/28/2003	4/28/2003	Relocation from Upton, NY	$ 142	
				TOTALS	$ 20,503	$ 4,581